Competency 1.1 **Radiation protection personnel shall demonstrate a working level knowledge of the various types of radiation and how they interact with matter.**

1. SUPPORTING KNOWLEDGE AND SKILLS

a. Describe each of the following forms of radiation in terms of structure, mass, origin, and electrostatic charge:
   - Alpha
   - Beta
   - Neutron
   - Gamma
   - X-Ray

b. Describe the interactions of the following with matter:
   - Charged particle interactions
     - Alpha particle
     - Beta particle (Positron annihilation and Bremsstrahlung)
   - Neutron interaction
     - Elastic scattering
     - Inelastic scattering
     - Fission
     - Capture, absorption, or activation
   - Photon interactions
     - Photoelectric effect
     - Compton scattering
     - Pair production

c. Discuss the shielding materials used for each of the above types of radiation and explain which are the best materials based on the interactions of radiation with matter.

d. Define "range" and describe the range energy relations of charged particles including:
   - Factors that affect the range of charged particles
   - Relative range of alpha and beta in air and tissue

e. Describe the attenuation of gamma and neutron radiation in shielding materials including:
   - Exponential attenuation
   - Build-up

f. Discuss radiation field characteristics for point, line, plane, and volume distributed sources.

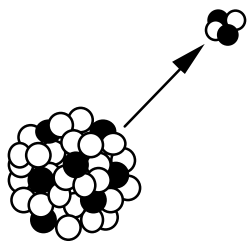
g. Describe the following particle ejection nuclear reactions and provide an example of each:

- Alpha, n
- Gamma, n
- n, Alpha

2. SUMMARY

Types of Radiation

Alpha Particles



Alpha radiation is particulate radiation emitted from the nucleus of an unstable atom. The alpha particle has a mass of 4 atomic mass units (amu) and consists of 2 protons and 2 neutrons. Since the alpha particle has 2 protons it has a positive charge of + 2. With few exceptions, only relatively heavy radioactive nuclides with an atomic number (Z) less than 82 will decay by alpha emission. Alpha radiation is monoenergetic, meaning its emissions are at discrete energies. The symbol α is used to designate alpha particles.

A nucleus emitting an alpha particle decays to a daughter element, reduced in Z by 2 and reduced in mass number (A) by 4. The standard notation for alpha decay is:

$$^{A}_{Z}X \rightarrow {}^{A-4}_{Z-2}Y + {}^{4}_{2}\alpha$$

For example, Radium-226 decays by alpha emission to produce Radon-222 as follows:

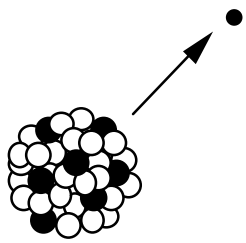
$$^{226}_{88}Ra \rightarrow {}^{222}_{86}Rn + {}^{4}_{2}\alpha$$

Alpha particles are the least penetrating of the three types of particulate radiation (alpha, beta, and neutron). They can be absorbed or stopped by a few centimeters of air or a sheet of paper.

Summary of alpha radiation:

- Are particulate radiations with relatively high energies (usually on the order of 4 to 5 MeV).
- Are positively charged helium nuclei consisting of 2 protons and 2 neutrons.
- Have a positive charge of +2.
- Have a mass of 4 amu.
- Have weak penetrating abilities because of large mass and high electrical charge.
- Alpha decay generally occurs in heavy atoms with masses greater than 200 amu.
- Are monoenergetic (i.e., have discrete energies).

Beta Particles



Beta radiation is particulate radiation in the form of an electron emitted from the nucleus of an unstable atom. The beta particle has a mass of 0.000548 amu and can have a negative charge of -1, beta minus particle or negatron (β^-), or a positive charge of +1, a beta plus particle or positron (β^+).

Atoms that emit β^- radiation do so because the nucleus has an excess number of neutrons. An excess number of neutrons can occur when atoms are bombarded with neutrons (called activation), or when heavy atoms fission to produce neutron-rich fission fragments. In β^- emitters, the nucleus of the parent gives off a negatively charged particle, resulting in a daughter more positive by one unit of charge. It has been postulated that a β^- particle is formed by the transformation of a neutron into a proton and electron. Because a neutron has been replaced by a proton, the Z number increases by one, but the A number is unchanged. There is also the emission of a neutrino (ν) or an antineutrino ($\bar{\nu}$) which are neutral (uncharged) particles with negligible rest mass. They travel at the speed of light, and are very non-interacting. They account for the energy distribution among positrons and beta particles from given radionuclides in the positron- and beta-decay processes respectively. Because they are so non-interacting, no energy is deposited in tissue and therefore no dose results to personnel exposed to neutrinos.

The standard notation for β^- decay is:

$$^{A}_{Z}X \rightarrow {}^{A}_{Z+1}Y + \beta^- + \nu$$

For example, lead-210 (Pb-210) decays by beta-minus emission to produce bismuth-210 (Bi-210) as follows:

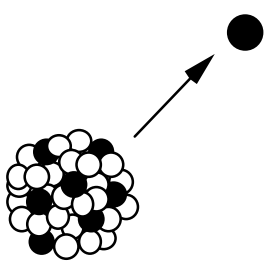
$$^{210}_{82}Pb \rightarrow {}^{210}_{83}Bi + \beta^- + \nu$$

Beta particles are emitted in a spectrum of kinetic energies ranging up to the maximum value of the decay energy, E_{max}. The average energy of beta particles is about $\frac{1}{3}E_{max}$. They travel several hundred times the distance of alpha particles in air (approximately 10 feet per MeV) and require a few millimeters of aluminum to stop them.

Proton-rich nuclei achieve stability by converting protons into neutrons. This results in the emission of a β^+. Positrons have only a transitory existence. The positive electron can be interacting, producing ionizations and excitations until it comes to rest. While at rest, the positron attracts a free electron, which then results in annihilation of the pair, converting both into electromagnetic energy. Two photons of 511 keV each arise at the site of the annihilation, accounting for the rest mass of the particles.

Summary of beta radiation:
- Particulate radiation.
- Have a negative charge of -1 for a β- particle.
- Have a positive charge of +1 for a β+ particle.
- Have a mass of 0.000548 amu.
- Have moderate range in matter, greater than an alpha particle.
- Have a continuous spectrum of energies.

Neutrons



Neutron radiation is particulate radiation, a neutron emitted from the nucleus of an unstable atom. The neutron particle has a mass of 1 amu and a charge of 0. Neutrons are emitted during the fissioning of a heavy atom, or are emitted from a nucleus of an atom that has been made unstable by the addition of energy in the form of particles or waves. Neutrons emitted from fissioning atoms have a spectrum of energies. Neutrons emitted by those atoms which have been bombarded by particles or waves tend to be monoenergetic. For example, take a thermal fission of uranium-235 (U-235):

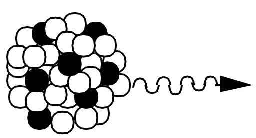
$$^{235}_{92}U + ^{1}_{0}n \rightarrow ^{141}_{55}Cs + ^{92}_{37}Rb + 3(^{1}_{0}n)$$

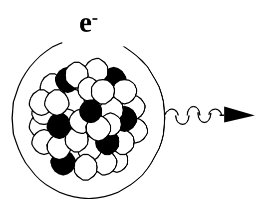
The neutrons given off in this reaction will have a spectrum of energies.

Summary of neutron radiation:

- Particulate radiation.
- Have no electrical charge.
- Have a mass of 1 amu.
- Have a wide range of energies ranging from thermal (0.025 eV) to fast (several MeV).
- Are very penetrating forms of radiation that travel indefinite distances in material.
- Occur from operating nuclear reactors, fission of heavy atoms, or neutron sources.

Gamma Rays and X-Rays





Gamma waves and x-rays are electromagnetic waves (photons) that travel at the speed of light and have no mass or electrical charge. The difference between gamma waves and x-rays is one of origin. Gamma waves are emitted from the nucleus of an unstable atom and x-rays are emitted from the electronic shell of an atom. Gamma wave emission does not change the number of protons or neutrons in the nucleus, but does rid the nucleus of excess energy. Most radioactive atoms emit photons in addition to other types of radiations. The most common types of radionuclides that emit gamma radiation are activation or fission products. No nuclide decays solely by gamma emission. Gamma waves are produced only to relieve excitation energy. They are emitted from nuclei of excited atoms following a radioactive transformation, and occur only after decay has occurred by alpha emission, beta emission, or electron capture. Although most nuclear decay reactions do have gamma emissions associated with them, there are some radionuclide species which decay by particulate emission with no gamma emission.

Summary of gamma and x-ray radiation:

- Are electromagnetic radiations (i.e., waves); photons.
- Have no mass.
- Have no electrical charge.
- Travel at the speed of light.
- Are very penetrating forms of radiation that travel indefinite distances in material because of the above properties.
- Have discrete energies.

Ionizing Radiation Interactions

Charged Particle Interactions

Charged particle radiations, such as alpha particles or electrons, will continuously interact with the electrons present in any medium through which they pass because of their electric charge. These particles must undergo an interaction resulting in a full or partial transfer of energy of the incident radiation to the electron or nuclei of the constituent atom. If the energy transferred to the electron is greater than the energy holding the electron to the atom, the electron will leave the atom and create ionization. Ionization is the process of turning an electrically neutral atom into an ion pair consisting of a negatively charged electron unbound to an atom, and an atom missing one electron creating a net positive charge. If insufficient energy is transferred to the electron to leave the atom, the electron is said to be excited. Excitation does not create ionization or ion pairs, but does impart some energy to the atom. In general, charged particles deposit energy in matter or interact by:

- Ionization
- Excitation
- Bremsstrahlung

Ionization

Ionization is any process which results in the removal of an electron (negative charge) from an electrically neutral atom or molecule by adding enough energy to the electron to overcome its binding energy. This leaves the atom or molecule with a net positive charge. The result is the creation of an ion pair made up of the negative electron and the positive atom or molecule. A molecule may remain intact or break-up, depending on whether an electron that is crucial to the molecular bond is affected by the event. Figure 1 schematically shows an ionizing particle freeing an L shell (the K shell is the closest to the nucleus, the L shell is the second shell) electron.

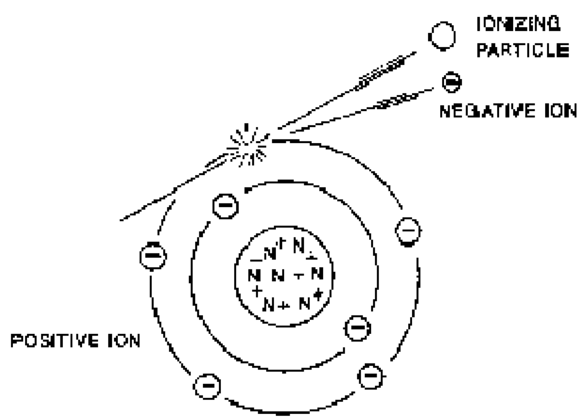


Figure 1 - Ionization

Excitation

Excitation is any process that adds enough energy to an electron, bound to an atom or molecule, so that it occupies a higher energy state (lower binding energy) than its lowest bound energy state (ground state). The electron remains bound to the atom or molecule, but depending on its role in the bonds of the molecule, molecular break-up may occur. No ions are produced and the atom remains electrically neutral. Figure 2 schematically shows an alpha particle (2 protons and 2 neutrons) exciting an electron from the K shell to the L shell because of the attractive electric force (assuming there is a vacant position available in the L shell).

Nuclear Excitation is any process that adds energy to a nucleon (nuclear particle, such as a neutron or a proton) in the nucleus of an atom so that it occupies a higher energy state (lower binding energy). The nucleus continues to have the same number of nucleons and can continue in its same chemical environment.

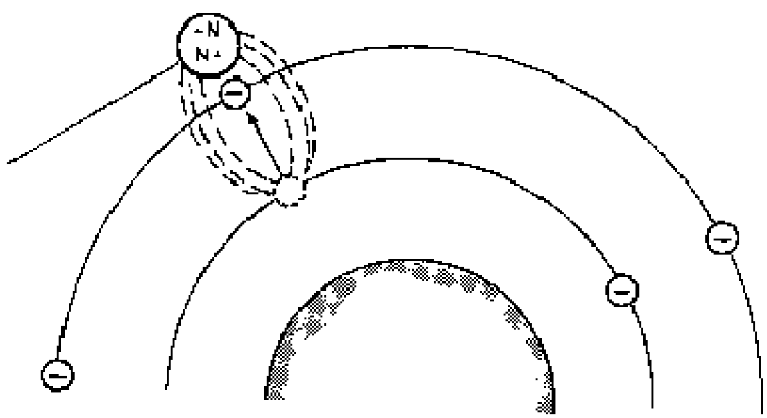


Figure 2 - Excitation

Bremsstrahlung

Bremsstrahlung, illustrated in Figure 3 on the following page, results from the interaction of a charged particle, such as a moving electron (negative charge), with the nucleus of an atom (positive charge) via the electric force field. The attractive force causes a radical deceleration of the electron, deflecting it from its original path. The kinetic energy that the electron loses is emitted as a photon (called an x-ray because it is created outside the nucleus). Bremsstralung has been referred to variously as "braking radiation," "white radiation," and "general radiation." Bremsstrahlung production is enhanced for high Z materials (larger coulomb forces) and high energy electrons (more interactions before all energy is lost).

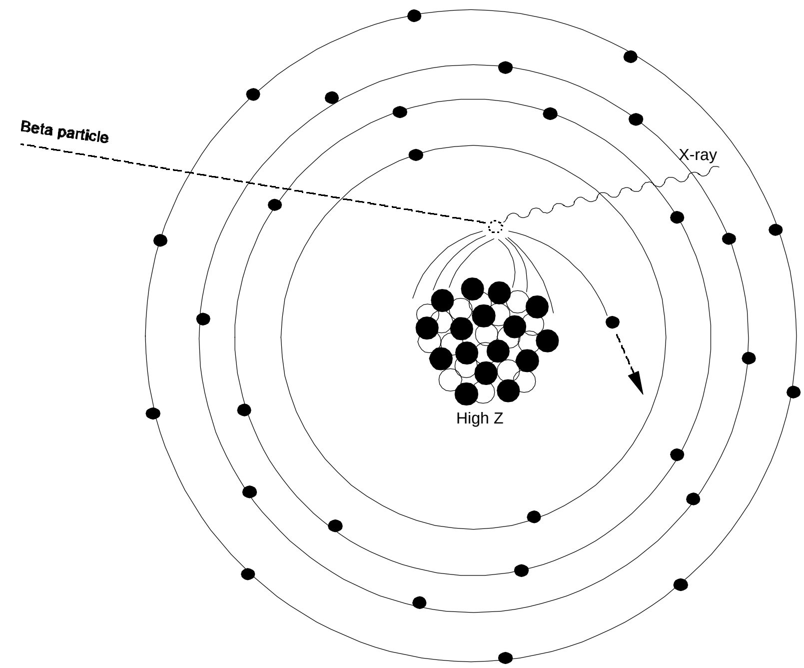


Figure 3 - Bremsstrahlung Radiation

For purposes of estimating bremsstrahlung hazard from beta radiation, the following approximate relationship may be used from Cember, 3rd edition, p.130:

$$f_\beta = 3.5 \times 10^{-4} ZE_m$$

where:
- f_β = the fraction of the incident beta energy converted into photons
- Z = atomic number of the absorber
- E_m = maximum energy of the beta particle, MeV.

Indirectly Ionizing Radiation

Radiations that have no electrical charge (gamma, x-rays, and neutrons) cannot interact with electrical fields created by electrons and protons. They must collide with these particles to interact. Since matter is made up of mostly empty space, electromagnetic radiation and neutrons are able to move freely through matter and have a small probability of interacting with matter. In contrast to directly ionizing radiation, as described above, uncharged radiation does not continuously lose energy by constantly interacting with the absorber. Instead, it may penetrate material and move through many atoms or molecules before it physically collides with an electron or nucleus. Indeed, in a chest x-ray, the image is the distribution of x-rays that made it to the film without interacting in the patient's chest. When they do interact, they produce directly ionizing particles (charged particles) that cause secondary ionizations. This type of radiation is called indirectly ionizing radiation. The probability of interaction is dependent upon the energy of the radiation and the density and atomic number of the absorber.

Photon Interactions

Gamma waves and x-rays are photons which differ only in their origin, and an individual x-ray cannot be distinguished from an individual gamma ray. Both are electromagnetic waves, and differ from radio waves and visible light waves only in having much shorter wavelengths. The difference in name is used to indicate a different source: gamma rays are of nuclear origin, while x-rays are of extra-nuclear origin (i.e., they originate in the electron cloud surrounding the nucleus). Both x-rays and gamma rays have zero rest mass, no net electrical charge, and travel with the speed of light. After photon radiation interacts via one of the following mechanisms, electrons are liberated from an atom. These electrons interact by ionization and excitation. There are three major mechanisms by which photons lose energy by interacting with matter:

The Photoelectric Effect

In the photoelectric effect the photon imparts all of its energy to an orbital electron of some atom. The photon, since it consisted only of energy in the first place, simply vanishes. Figure 4 schematically shows a photoelectric interaction. The energy is imparted to the orbital electron in the form of kinetic energy of motion, overcoming the attractive force of the nucleus for the electron (the binding energy) and usually causing the electron to fly from its orbit with considerable velocity. Thus, an ion pair results.

The high velocity electron, which is called a photoelectron, is a directly ionizing particle and typically has sufficient energy to knock other electrons from the orbits of other atoms. It goes on its way producing secondary ion pairs until all of its energy is expended. The probability of photoelectric effect at its maximum occurs when the energy of the photon is equal to the binding energy of the electron. The tighter an electron is bound to the nucleus, the higher the probability of photoelectric effect, so most photoelectrons are inner-shell electrons. The photoelectric effect is seen primarily as an effect of low energy photons with energies near the electron binding energies of materials and high Z materials whose inner-shell electrons have high binding energies.

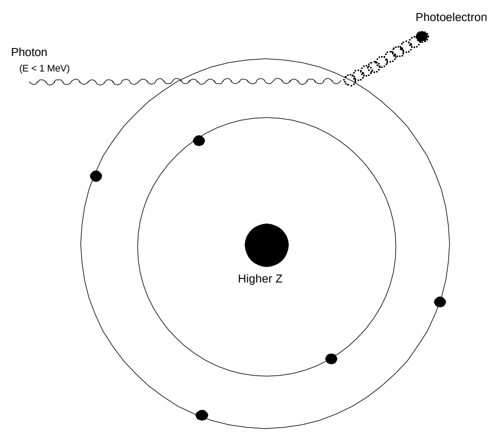


Figure 4 - Photoelectric Effect

Compton Scattering

In Compton scattering there is a partial energy loss for the incoming photon. The photon interacts with an orbital electron of some atom and only part of the photon energy is transferred to the electron. Figure 5, below, schematically shows a Compton scattering (also called Compton interaction).

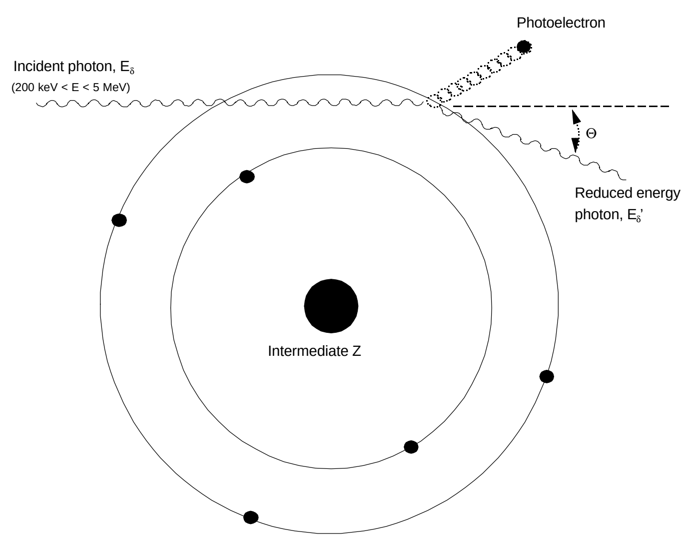


Figure 5 - Compton Scattering

After the collision the photon is deflected in a different direction at a reduced energy. The recoil electron, now referred to as a Compton electron, produces secondary ionization in the same manner as does the photoelectron, and the "scattered" photon continues on until it loses more energy in another photon interaction. By this mechanism of interaction, photons in a beam may be randomized in direction and energy, so that scattered radiation may appear around corners and behind "shadow" type shields. The probability of a Compton interaction increases for loosely bound electrons and, therefore, increases proportionally to the Z of the material. Most Compton electrons are valence electrons. Compton scattering is primarily seen as an effect of medium energy photons and its probability decreases with increasing energy. For the figure above, it can be shown that:

$$E_\gamma^{/} = \frac{E_\gamma}{1 + \left[\left(\frac{E_\gamma}{m_0 c^2}\right)(1 - \cos\,\theta^0)\right]}$$

where: $m_o c^2$ = 511 keV (the rest mass energy of the electron).

Pair Production

Pair production occurs when the photon is converted to mass. This conversion of energy to mass only occurs in the presence of a strong electric field, which can be viewed as a catalyst. Such strong electric fields are found near the nucleus of atoms and are stronger for high Z materials. Figure 6 schematically shows pair production and the fate of the positron when it combines with an electron (its anti-particle) at the end of its path.

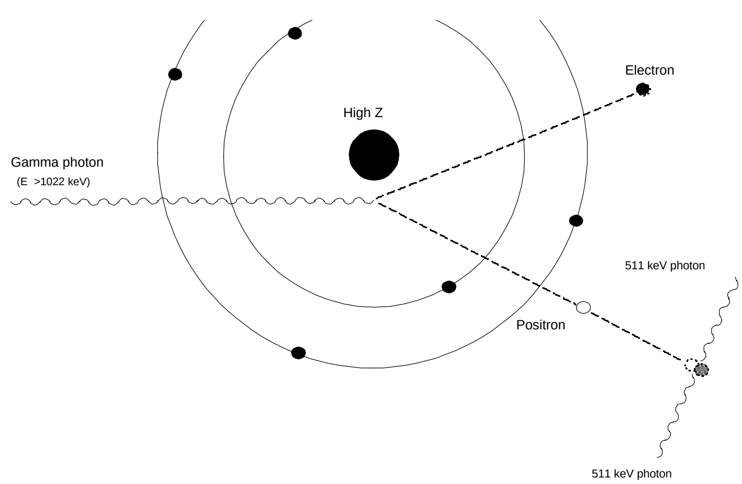
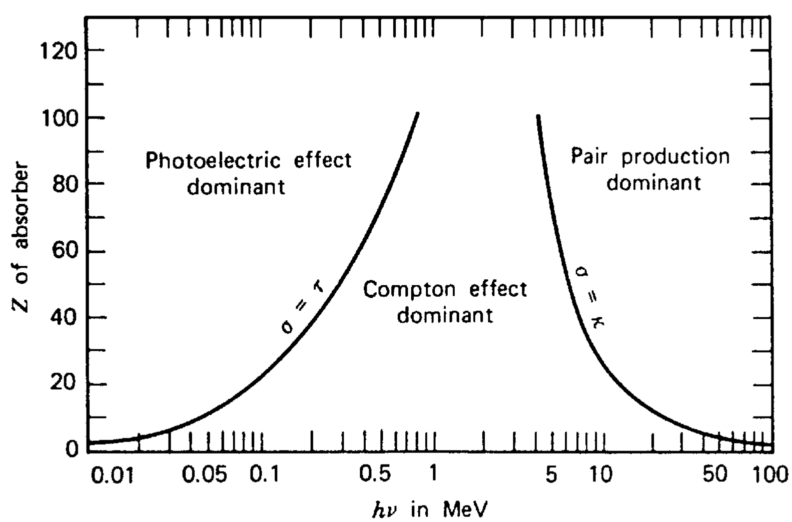


Figure 6 - Pair Production and Annihilation

In pair production a photon simply disappears in the vicinity of a nucleus and in its place appears a pair of electrons: one negatively and one positively charged (anti-particles are also called electron and positron respectively). The mass of these electrons has been created from the pure energy of the photon, according to the familiar Einstein equation $E = mc^2$, where (E) is energy in joules, (m) is mass in kilograms, and (c) is the velocity of light in m/sec. **Pair production is impossible unless the photon possesses greater than 1022 keV of energy to make up the rest mass of the particles.** Any excess energy in the photon above the 1022 keV required to create the two electron masses is simply shared between the two electrons as kinetic energy of motion, and they fly out of the atom with great velocity. The probability increases for high Z materials and high energies.

The pair production electron travels through matter, causing ionizations and excitations, until it loses all of its kinetic energy and is joined with an atom. The positive electron (known as a positron) also produces ionizations and excitations until it comes to rest. While at rest, the positron attracts a free electron, which then results in annihilation of the pair, converting both into electromagnetic energy. Thus, two photons of 511 keV each arise at the site of the annihilation (accounting for the rest mass of the particles). The ultimate fate of the annihilation photons is either photoelectric absorption or Compton scattering followed by photoelectric absorption.

The following figure shows the values of Z (different absorber material) and hv (photon energy). This relationship illustrates the areas defined within which photoelectric absorption, Compton scattering, and pair production predominate. As shown in the graph, pair production is confined to high-energy photon interactions. (From *The Atomic Nucleus* by R.D. Evans, 1955, McGraw-Hill Book Company.)



Neutron Interactions

The neutron has a mass number of 1 and no electrical charge. Because the neutron has no electrical charge the neutron has a high penetrating ability in matter. In order to interact the neutron must collide with a massive object such as the nucleus of an atom. Electrons, because they are only about 1/1800 the mass of a neutron, do not slow down or deflect a neutron. Therefore, neutron interactions are governed by the velocity or kinetic energy of the neutron and the size of the target nucleus.

When neutrons are classified by their kinetic energies into various categories, frequently the energy ranges and names given to each neutron energy range is determined by the materials being used or research being conducted. For example, reactor physics, weapons physics, accelerator physics, and radiobiology each have generated a classification system that serves their needs. Typically the only category common to them all is thermal. The classification used for neutron interaction in tissue is:

Category	Energy Range
Thermal	~ 0.025 eV ($\lesssim$ 0.5 eV)
Intermediate	0.5 eV to 100 keV
Fast	100 keV to 20 MeV
Relativistic	> 20 MeV

One should be familiar with the classification of neutrons by energy that applies to the area where they are working so no confusion arises when using terminology.

Classification of neutrons according to kinetic energy is important from two standpoints: (a) the interaction of neutrons with the nuclei of atoms differs with the neutron energy, and (b) the methods of producing, detecting and shielding against the various classes of neutrons are different.

Neutron Reactions

When describing neutron reactions with a nucleus, the standard notation is (n,γ) where n is the initial neutron and γ is the resulting wave following the interaction with nucleus. Radiative capture with gamma emission is the most common type of reaction for slow neutrons. This (n,γ) reaction often results in product nuclei which are radioactive. For example:

$$^{59}_{27}\mathrm{Co} + ^{1}_{0}\mathrm{n} \text{---->} ^{60}_{27}\mathrm{Co} + \gamma$$

This process of converting a stable nucleus to its radioactive counterpart by neutron bombardment is called "neutron activation." Many radionuclides used in nuclear medicine are produced by this process.

A second type of general reaction for slow neutrons is that giving rise to charged particle emission. Typical examples include (n,p), (n,d), and (n,α) reactions (i.e., a reaction in which a proton, a deuteron, or an alpha particle is ejected from the target nucleus.) An example is given below:

$$^{10}_{5}B + ^{1}_{0}n \text{ ---> } ^{7}_{3}Li + ^{4}_{2}\alpha$$

A third type of neutron-induced nuclear reaction is fission. Fission occurs following the absorption of a slow neutron by several of the very heavy elements. When uranium-235 (U-235) nuclei undergo fission by neutrons, an average of 2 to 3 neutrons are expelled along with associated gamma radiation. The nucleus splits into two smaller nuclei which are called primary fission products or fission fragments. These products usually undergo radioactive decay to form secondary fission product nuclei. As an example, if one neutron fissions a U-235 nucleus, it could yield yttrium-95 (Y-95), iodine-139 (I-139), two neutrons and fission energy. There are some 30 different ways that fission may take place with the production of about 60 primary fission fragments. These fragments and the atoms which result from their decay are referred to as fission products, and they number between 400 and 600, according to the type and number of nucleons their nuclei possess.

Many fission products have found application in medicine, industry, and research. A well known example is iodine-131(I-131) which is used extensively in medicine as both a diagnostic and therapeutic agent.

The fission process is the source of energy for nuclear reactors and some types of nuclear weapons. Also, neutrons generated from the fissioning of the fuel in a reactor are used to activate stable materials to a radioactive form as previously discussed. Many radioisotopes used in medicine are produced by neutron activation in this manner.

Elastic and Inelastic Scattering

Neutron scattering is a fourth type of interaction with the nucleus. This description is generally used when the original free neutron continues to be a free neutron following the interaction. Scattering is the dominant process for fast neutrons when the neutron is moving too fast to become a part of a nucleus. Multiple scattering by a neutron is the mechanism of slowing down or moderating fast neutrons to thermal energies. This process is sometimes called thermalizing fast neutrons.

Elastic scattering occurs when a neutron strikes a nucleus (typically of approximately the same mass as that of the neutron) as schematically shown in Figure 7, on the following page. Depending on the size of the nucleus, the neutron can transfer much of its kinetic energy to that nucleus which recoils off with the energy lost by the neutron. Hydrogen causes the greatest energy loss to the neutron because the single proton in the nucleus is the same mass as the neutron. The process is analogous to the rapid dissipation of the energy of a cue ball when it hits other balls of equal mass on a billiard table. During elastic scattering reactions, it is worth noting, no gamma radiation is given off by the nucleus. The recoil nucleus can be knocked away from its electrons and, being positively charged, can cause ionization and excitation.

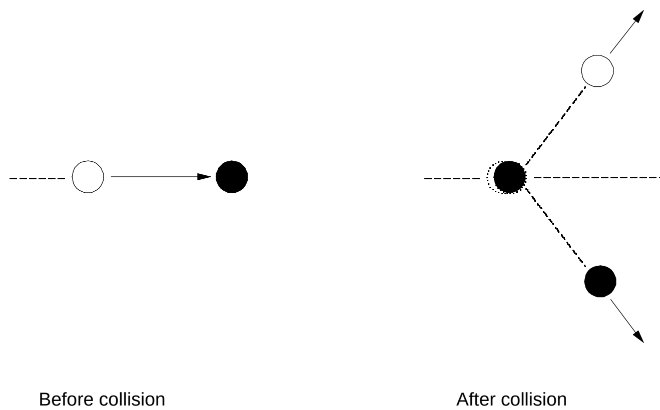


Figure 7 - Elastic Scattering

Inelastic scattering occurs when a neutron strikes a large nucleus as schematically shown in Figure 8. The neutron penetrates the nucleus for a short period of time, transfers energy to a nucleon inside, and then exits with a small decrease in energy. The nucleus is left in an excited state, emitting gamma radiation which can cause ionization and/or excitation.

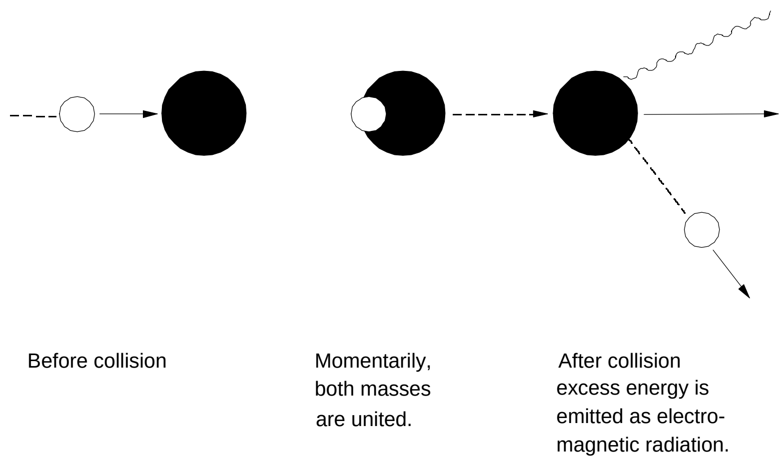


Figure 8 - Inelastic Scattering

Radiation Shielding

Alpha particles are relatively massive, slow moving particles that interact by ionization and excitation. Therefore, alpha radiation is not very penetrating. Alpha radiation is not an external hazard and can be shielded by a:

- Few inches of air
- Sheet of paper
- Dead layer of skin

Beta particles are relatively light, fast moving particles that interact by ionization and excitation. Beta radiation is moderately penetrating dependant on the energy or velocity of the beta particle, and can be an external hazard if it can penetrate the dead layer of skin. Beta radiation should be shielded by low atomic number materials (i.e., Z) to prevent the production of bremsstrahlung radiation. These materials include:

- Plastic
- Wood
- Aluminum

Neutron shielding involves slowing down fast neutrons and absorbing thermal neutrons. For example, control rods in nuclear reactors can be fabricated from boron, which is a good material to absorb thermal neutrons. Neutron shielding is highly dependant on the energy of the neutron. The goal in neutron shielding is to generate a charged particle via an interaction. The best interaction for shielding neutrons would be an elastic collision with a light nucleus such as a hydrogen atom. A hydrogen nucleus consists of a single proton and allows a significant transfer of energy to a proton because the masses of the proton and neutron are almost the same. The neutron collides with the proton, transferring energy and recoils the proton away from its electron cloud. The liberated proton's range is then very short, causing ionizations and excitations along the recoiled proton's path. Neutrons can be shielded by materials with a high hydrogen content such as:

- Water
- Concrete
- Plastic
- Fuel Oil
- Paraffin

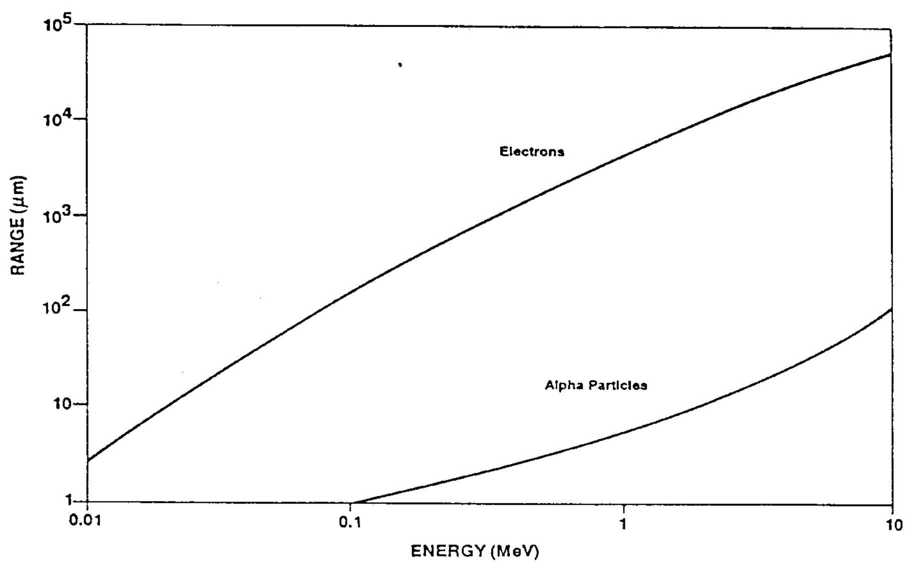
Photon shielding is also highly dependant on the energy of the photon and the Z number of the shielding material. As in neutron shielding, the goal is to produce a charged particle via an interaction, preferably the photoelectric effect, in which all of the photon energy is transferred to the electron. The photoelectron's range in matter is very short, causing ionizations and excitations in the shielding material. The energy of the photon is then transferred to the shield by photoelectrons. Since photons interact with electrons, photons can be shielded by any material which provides an adequate number of electrons. This can be done by use of high atomic number (high Z) material, such as lead or uranium. If space is not limited, water or concrete may be a practical shielding material.

Charged Particle Range

Charged particles have a definite range in matter. The range of a charged particle in an absorber is the average depth of penetration of the charged particle into the absorber before it loses all of its kinetic energy and stops. The energy of the particle, which is a function of the mass of the particle and its velocity, and the electrical charge of the particle affect the range of the charged particle in a material. The atomic density (number of atoms per cubic centimeter) and the atomic number (Z) of the shielding material also affect range. Generally, the higher the electrical charge and the higher the mass, the shorter the range of the charged particle. Conversely, the lighter the mass and the smaller the electrical charge, the longer the range. Alpha particles have a range in air of 2 to 3 inches. In tissue, alpha particles have a range of 70 to 100 µm. The range of most alpha particles is such that they cannot penetrate the dead layer of skin.

The factor that effects the range of a charged particle in any material is a unit called density-thickness. Density-thickness can be calculated by multiplying the density of a material in grams per cubic centimeter (g/cm^3) by the distance the particle traveled in that material in centimeters. The product is density-thickness in units of grams per square centimeter (g/cm^2). Density-thickness can be considered a cross-sectional target for a charged particle as it travels through the material.

The concept of density-thickness is important to discussions of beta radiation attenuation by human tissue, detector shielding/windows, and dosimetry filters. Although materials may have different densities and thicknesses, if their density-thickness values are the same, they will attenuate beta radiation in a similar manner. For example, a piece of Mylar used as a detector window with a density of 7 mg/cm^2 will attenuate beta radiation similar to the outer layer of dead skin of the human body which has a density-thickness of 7 mg/cm^2.



The above figure is from *Health Risks of Radon and Other Internally Deposited Alpha-Emitters*; (BEIR IV, c. 1988 by the National Academy of Sciences, National Academy Press, Washington, DC). This figure shows the range of alpha particles in soft tissue of unit density.

Density-thickness values for the human body can be calculated for the skin of the whole body (0.007 cm), the lens of the eye (0.3 cm), and the whole body (1.0 cm, deep tissue). The density of soft human tissue is equal to 1,000 milligrams per cubic centimeter (mg/cm^3) (ICRP 15). Therefore, the density-thickness values for the skin, lens of the eye and whole body are 7 milligrams per square centimeter (mg/cm^2), 300 mg/cm^2 and 1,000 mg/cm^2.

These values can be used to design radiation detection instrumentation such that detector windows and shields have the same, or similar, density-thickness values. For example, some instruments use a detector window of 7 mg/cm^2. Any beta radiation passing through the detector window would also pass through the outer layer of dead skin on the human body and deposit energy in living tissue of the skin. External dosimetry can be designed around these values such that dose equivalent is determined for the skin, lens of the eye, and the whole body. For example, a dosimeter filter may be designed as 1,000 mg/cm^2. Any radiation passing through this filter would deposit energy in deep tissue.

Beta particles have a range in air of about 10 feet per MeV of kinetic energy. Beta particles can penetrate the dead layer of skin if they possess more than 0.07 MeV of kinetic energy.

Gamma, X-Ray, and Neutron Attenuation

When shielding against x-rays and gamma rays, it is important to realize that photons are removed from the incoming beam on the basis of the probability of an interaction (photoelectric, Compton, or pair production). This process is called attenuation and can be described using the "linear attenuation coefficient," μ, which is the probability of an interaction per path length x through a material. The linear attenuation coefficient varies with photon energy and type of material. Mathematically, the attenuation of a narrow beam of monoenergetic photons is given by:

$$I(x) = I_o e^{-\mu x}$$

where:

where:	$I(x)$	=	Radiation intensity exiting a material of thickness x
	I_o	=	Radiation intensity entering a material
	e	=	Base of natural logarithms (2.714......)
	μ	=	Linear attenuation coefficient
	x	=	Thickness of material

This equation shows that the intensity is reduced exponentially with thickness. I(x) never actually equals zero because x-rays and gamma rays interact based on probability and there is a finite (albeit small) probability that a gamma could penetrate through a thick shield without interacting. Shielding for x-rays and gamma rays then becomes an ALARA issue and not an issue of shielding to zero intensities.

The formula above is used to calculate the radiation intensity from a narrow beam behind a shield of thickness x, or to calculate the thickness of absorber necessary to reduce radiation intensity to a desired level. Tables and graphs are available which give values of μ determined experimentally for different radiation energies and many absorbing materials. The larger the value of μ the greater the reduction in intensity for a given thickness of material. The fact that lead has a high μ for x- and gamma radiation is partially responsible for its wide use as a shielding material.

Although attenuation of the initial beam of photons occurs by photoelectric, Compton, and pair production, photons can be scattered by Compton interactions. If the beam is broad, generally considered to be a poor geometry condition, photons can be scattered into the area one is trying to shield. The scattered photons are accounted for by a build up factor, B, in the attenuation equation as follows:

$$I = B I_0 e^{-ux}$$

where: B = the buildup factor which is always greater than 1

Tables of dose build-up factors (indicating that the increased radiation intensity is to be measured in terms of dose units) can be found in the *Radiological Health Handbook*, Revised Edition.

The buildup is mostly due to Compton scatter. Scattered radiation is present to some extent whenever an absorbing medium is in the path of radiation. Frequently, room walls, the floor, and other solid objects are near enough to a source of radiation to make scatter appreciable. When a point source is used under these conditions, the inverse square law is no longer completely valid for computing radiation intensity at a distance. Measurement of the radiation is then necessary to determine the potential exposure at any point.

Fast neutrons are poorly absorbed by most materials and the neutrons merely scatter through the material. For efficient shielding of fast neutrons, one needs to slow them down and then provide a material that readily absorbs slow neutrons.

Since the greatest transfer of energy takes place in collisions between particles of equal mass, hydrogenous materials are most effective for slowing down fast neutrons. Water, paraffin, and concrete are all rich in hydrogen, and thus important in neutron shielding. Once the neutrons have been reduced in energy, typically either boron or cadmium is used to absorb the slowed neutrons.

Borated polyethylene is commonly available for shielding of fast neutrons. Polyethylene is rich in hydrogen and boron is distributed, more or less, uniformly throughout the material to absorb the slowed neutrons that are available. When a boron atom captures a neutron, it emits an alpha particle, but because of the extremely short range of alpha particles, there is no additional hazard.

A shield using cadmium to absorb the slowed neutrons is usually built in a layered fashion. Neutron capture by cadmium results in the emission of gamma radiation. Lead or a similar gamma absorber must be used as a shield against these gammas. A complete shield for a capsule type neutron source may consist of, first, a thick layer of paraffin to slow down the neutrons, then a surrounding layer of cadmium to absorb the slow neutrons, and finally, an outer layer of lead to absorb both the gammas produced in the cadmium and those emanating from the capsule.

Rather than using linear or mass absorption coefficients, the **microscopic** cross section (σ) is used to describe the ability of a given absorber to remove neutrons from a beam, and is given in either cm^2 or in a unit called the *barn (b)*. One barn equals 10^{-28} m^2. The cross section denotes the target size an atom has to a bombarding particle. It is not actually an area, but rather a probability that a reaction will occur. The **macroscopic** cross section, Σ, equals the number of absorber atoms per cm^3 (N) multiplied by the microscopic cross section, σ, such that:

$$\Sigma = N\sigma$$

The attenuation of a narrow beam of monoenergetic neutrons passing through a material follows an exponential relationship given by the following equation:

$$\phi(x) = \phi_o e^{-\Sigma x}$$

where:	$\phi(x)$	=	Neutron flux exiting a material of thickness x
	ϕ_o	=	Neutron flux entering a material
	Σ	=	Total macroscopic cross section
	x	=	Thickness of material

Tables and data for the total macroscopic cross section can be found in the *Radiological Health Handbook*, Revised Edition.

Radiation Field Characteristics

Point Sources

The intensity of the radiation field decreases as the distance from the source increases. Therefore, increasing the distance will reduce the amount of exposure received. In many cases, especially when working with point sources, increasing the distance from the source is more effective than decreasing the time spent in the radiation field.

Theoretically, a point source is an imaginary point in space from which all the radiation is assumed to be emanating. While this kind of source is not real (all real sources have dimensions), any geometrically small source of radiation behaves as a point source when one is within three times the largest dimension of the source. Radiation from a point source is emitted equally in all directions. Thus, the photons spread out to cover a greater area as the distance from the point source increases. The effect is analogous to the way light spreads out as we move away from a single source of light, such as a light bulb.

The radiation intensity for a point source decreases according to the **Inverse Square Law** which states that as the distance from a point source decreases or increases the dose rate increases or decreases by the square of the ratio of the distances from the source. The inverse square law becomes inaccurate close to the source (i.e., within three times the largest dimension of the source).

As previously mentioned, the exposure rate is inversely proportional to the square of the distance from the source. The mathematical equation is:

$$I_1(d_1)^2 = I_2(d_2)^2$$

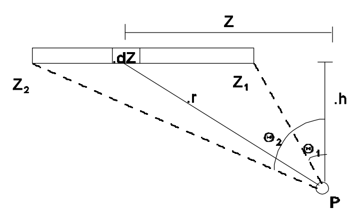
where:
- I_1 = exposure rate at 1st distance (d_1)
- I_2 = exposure rate at 2nd distance (d_2)
- d_1 = 1st (known) distance
- d_2 = 2nd (known) distance

This equation is assuming the attenuation of the radiation in the intervening space is negligible and the dimensions of the source and the detector are small compared with the distance between them.

The inverse square law holds true only for point sources; however, it gives a good approximation when the source dimensions are smaller than the distance from the source to the exposure point. Due to distance constraints, exposures at certain distances from some sources, such as for a pipe or tank, cannot be treated as a point source. In these situations, these sources must be treated as line sources or large surface sources.

Line Sources

An example of a line source would be a pipe carrying contaminated cooling water or liquid waste, a control rod, a series of point sources which are close together, or a needle injecting a radioisotope into tissue. With line sources, an assumption must be made that the distribution of radioactivity is uniform throughout the source. When no attenuator is present, the relationship between the line source emission rate and the flux at the receptor (P) depends on the location of the receptor with respect to the line source. However, this relationship is more complex mathematically than in the case of the point source, and the use of calculus is required. The following figure and formula applies to line sources.



where: S = source emission rate (photon per second per cm)
Φ = flux at the receptor (photon per cm^2 per second)
r = distance from the source to the receptor P
Θ = angle in radians
Z = length of the line source in cm

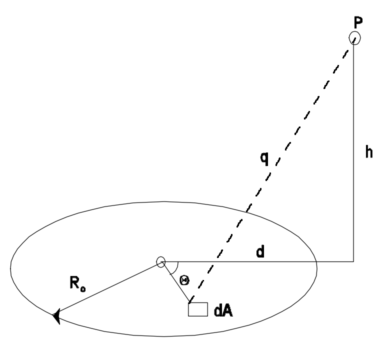
$$\Phi = \int_{Z_1}^{Z_2} \frac{S(dZ)}{4\pi r^2}$$

$$\Phi = \frac{S}{4\pi h}\,(\Theta_2 - \Theta_1)$$

For a detailed discussion of line source calculations, see Cember, 3rd ed., pp. 421-423.

Plane Sources

An example of a plane source would be a spill of liquid containing radioactivity on the floor. Again, when estimating the amount of radioactivity emanating from an area source, an assumption must be made that the distribution of radioactivity is uniform throughout the source. For an area source with an attenuator present, the calculations become very complicated. For illustrative purposes, an example of a circular area source without an attenuator present is given.



$$\Phi = \int \frac{S_A}{4\pi q^2}\, dA$$

$$\Phi = \frac{S_A}{4} \ln \left[\frac{R_o^2 + h^2 - d^2 + \sqrt{(R_o^2 + h^2 - d^2)^2 + 4d^2h^2}}{2h^2}\right]$$

And in the special case where P is on the axis of the circular area, d = 0 and:

$$\Phi = \frac{S_A}{4} \ln \left[\frac{R_o^2 + h^2}{h^2}\right]$$

where:
- S_A = source emission rate (photon per second per cm^2)
- Φ = flux at the receptor (at point P)
- R_o = distance from the source to the receptor P
- Θ = angle in radians

For area sources or volumetric sources such as a large cylindrical or rectangular tank or any other type of geometry where the width or diameter is small compared to the length, the following rules can apply:

- When the distance to an area source is small compared to the longest dimension, then the exposure rate falls off a little more slowly than 1/d (i.e., not as quickly as a line source).
- As the distance from an area source increases, then the exposure rate drops off at a rate approaching $1/d^2$.
- In most cases volumemetric sources of radiation are considered the same as plane sources for estimating the radiation field.

The exposure rate versus distance calculations can be used to make an estimate of the radiation intensity at various distances. These estimates are valuable tools to approximate and verify the readings obtained from exposure rate meters.

Nuclear Reactions Generating Particles

There are radionuclides which occur as a result of various **man-made** reactions. These are called artificial radionuclides. The process of changing an element into a different element is sometimes called transmutation. Transmutation may induce radiation to be emitted from the nucleus. There are three methods of artificially transmutating elements, they are bombardment of the nucleus with:

- Charged particles
- Neutrons (called activation)
- High energy photons

The vast majority of artificially produced radionuclides are produced by one of the above processes. In general, induced radiation may occur if the incident radiation on the nucleus exceeds the binding energy of the target nucleus.

It was determined in 1934 that induced transmutations could produce nuclei which were residually unstable in somewhat the same manner as naturally occurring radionuclides. Irene Curie and Frederic Joliot reported that certain light elements (boron, magnesium, aluminum), when bombarded with alpha particles, continued to emit radiation for a finite time after bombardment had stopped. The following reaction, involving aluminum bombarded with alpha particles, was the first reported instance of artificial, or induced radioactivity:

$$^{27}_{13}\mathrm{Al} + {}^{4}_{2}\alpha \rightarrow {}^{30}_{15}\mathrm{P} + {}^{1}_{0}\mathrm{n}$$

The resultant nucleus $^{30}_{15}\mathrm{P}$ was observed to be radioactive, emitting a small charged particle and reaching stability within minutes.

By subjecting a stable nucleus to neutron bombardment, some of the neutrons may be absorbed into the nucleus changing the neutron to proton ratio and causing radiation to be emitted from the nucleus. These reactions are called neutron activation or charged particle emission. An example of neutron activation is:

$$^{59}_{27}\mathrm{Co} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{60}_{27}\mathrm{Co} + \gamma$$

The following is an example of charge particle emission that is also used in neutron detectors.

$$^{10}_{5}\mathrm{B} + {}^{1}_{0}\mathrm{n} \rightarrow {}^{7}_{3}\mathrm{Li} + {}^{4}_{2}\alpha$$

Radioactivity can be induced by very energetic photons which exceed the binding energy of the nucleus. The following are examples of photo-neutron emission generally found at accelerators.

$$^{16}_{8}O + \gamma \rightarrow {}^{15}_{8}O + {}^{1}_{0}n$$
$$^{14}_{7}N + \gamma \rightarrow {}^{13}_{7}N + {}^{1}_{0}n$$

Radioactivity can also be induced by bombarding the nucleus with very energetic alpha particles. A common example is plutonium and beryllium which is used as a neutron calibration source. The plutonium supplies the alpha particle via decay. The reaction is:

$$^{9}_{4}Be + {}^{4}_{2}\alpha \rightarrow {}^{12}_{6}C + {}^{1}_{0}n$$

3. SELF-STUDY SCENARIOS/ACTIVITIES AND SOLUTIONS

Activity 1, (solutions to all activities can be found on p. RP 1.1-29)

Calculate the energy of a cesium-137 (662 keV) gamma ray following Compton scattering with an electron at an angle of 180^{o}.

Your Solution:

Activity 2

a. A neutron with an initial kinetic energy of 10 keV collides with a target nucleus. The neutron then elastically scatters with a kinetic energy of 6 keV. What is the kinetic energy of the recoil nucleus?

b. A fast neutron with a kinetic energy of 5 MeV scatters inelastically with a target nucleus. The nucleus recoils with a kinetic energy of 0.4 MeV and emits a 0.2 MeV gamma ray. What is the energy of the scattered neutron?

Your Solution:

Activity 3

A point source, which decays by beta-minus emission, has a maximum energy value where E_{max} = 1.2 MeV. If this source was encapsulated in 100 mg/cm^2 of a low Z material, would you expect the average beta (E_{ave}) to change, and if so, how? Is it desirable to encapsulate beta sources with low or high Z material and why?

Your Solution:

Activity 4

A narrow beam of 40 keV photons containing 750,000 photons is passed through 3 mm of copper (Cu). From the *Radiological Health Handbook*, Revised Edition, you find the mass attenuation coefficient to be 4.8610 cm^2/g, and the density of Cu to be 8.94 g/cm^3. How many photons are attenuated in the Cu?

Your Solution:

Activity Solutions:

Activity 1, Solution

$$E'_\gamma = \frac{662}{1 + \left[\left(\frac{662}{511}\right)(1 - \cos 180^0)\right]}$$

E'_γ = **184.3 keV**

Activity 2, Solution

a. $E_T = E_n - E'_n$
$= 10\text{ keV} - 6\text{ keV}$
$=$ **4 keV**

b. $E'_n = E_n - E_T - E_\gamma$
$= 5\text{ MeV} - 0.4\text{ MeV} - 0.2\text{ MeV}$
$=$ **4.4 MeV**

Activity 3, Solution

E_{ave} will become higher because the lower beta energies are attenuated in the encapsulation. It is desirable to encapsulate or shield beta sources in low Z material to reduce the production of bremsstrahlung radiation.

Activity 4, Solution

First determine the linear attenuation coefficient:

$$\mu = (4.8610\text{ cm}^2/\text{g})(8.94\text{ g/cm}^3) = 43.46\text{ cm}^{-1}$$

Then using the equation from p. RP1.1-19:

$$I_x = I_o e^{-\mu x} = (750{,}000\text{ photons})e^{-(43.46\text{cm-1})(0.3)} = 1.632\text{ photons}$$

Therefore, the number of photons attenuated in the 3 mm of Cu is:

= 750,000 photons - 1.632 photons
= **<u>749,998 photons</u>**

4. SUGGESTED ADDITIONAL READINGS AND/OR COURSES

Readings

- Argonne National Laboratory. (1988). *Department of Energy Operational Health Physics Training* (ANL-88-26). Argonne, IL.
- Cember, Herman. (1996). *Introduction to Health Physics* (3rd ed.). McGraw-Hill: New York.
- Gollnick, Daniel A. (1991). *Basic Radiation Protection Technology* (2nd ed.). Pacific Radiation Corporation: Altadena, CA.

Courses

- *Applied Health Physics* -- Oak Ridge Institute for Science and Education.
- *Health Physics for the Industrial Hygienist* -- Oak Ridge Institute for Science and Education.
- *Radiological Worker Training* -- DOE-EH.
- *Radiological Control Technician* -- DOE-EH.
- *Safe Use of Radionuclides* -- Oak Ridge Institute for Science and Education.
- *Radiation Protection General Technical Base Qualification Standard Training* -- GTS Duratek.
- *Nuclear Physics/Radiation Monitoring* -- DOE.
- DOE/EH-0450 (Revision 0), *Radiological Assessors Training (for Auditors and Inspectors) - Fundamental Radiological Control,* sponsored by the Office of Defense Programs, DOE.